LIQUID ROCKET COMBUSTION PROCESSES

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TASK III

Preliminary Review of Major Information Gaps

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FOREWORD

Progress Report on Task III "Preliminary Review of Major Information Gaps"

This is the third task on the engineering study "Literature Survey and Analysis of Liquid Propellant Rocket Engine Combustion Processes".

ABSTRACT

A preliminary review of major information gaps is presented herein. This presentation is based on preliminary reviews on approximately 5,000 article abstracts against the preliminary outline presented as the summary of Task II in the previous report of this series. In few of the areas does there appear to be adequate detail to completely fill in the outline as presented.

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TASK STATMENT

ABSTRACT OF PROGRAM STATEMENT

This effort has been analyzed and set up in nine tasks. A literature search and analysis program has an initial search and acquistion effort followed by a period of intensive review and analysis.

The Preliminary Tasks Are:

I Initiate the Survey
II Set Up Preliminary Accounting Outline
III Prepare Preliminary Review of Major Information Gaps

Intensive Review and Analysis Tasks Are:

IV Combustion Processes
V Combustion Supported Waves
VI Stream Break-up
VII Flow, Dispersion and Mixing
VIII Completion of Descriptive Accounting Outline
IX Assembly of all Elements into an Intergrated Picture

TASK III

PRELIMINARY REVIEW OF INFORMATION GAPS

This task is the preparation of a preliminary review of apparent information gaps. This will be accomplished by comparison of the information available in the abstracts which have been collected to date against the preliminary accounting outline as presented in the previous report. This will serve two purposes:

1. It will point up those areas where a more diligent search effort maybe required and
2. It will point out those areas in which additional work is required even on the basis of this preliminary review.

DISCUSSION

REVIEW OF MODEL

In a rocket chamber a very large number of events are happening simultaneously. Each of these events has its own series of antecedents and in turn is likely to affect a series of following events. All of these events are influenced, and some of them are dominated, by the manner in which phenomena are going on around them or preceding them. Finally, these phenomena are not uniformly distributed in space or in time sequence. A model must then be capable of presenting the diverse situations which are occurring in the rocket chamber over some depth of time. The model must be capable of developing both the geometrical distribution of chamber contents and phenomena but also the temperal sequence by which these distributions of materials and their reactions occur.

It has been decided to take a Stokesian approach and follow successive and identifiable gas elements as they are generated, accrue mass and energy, and are accelerated down the chamber. Such an element will over-take stream and droplet fields, take up mass through the evaporation of these condensed phase element, exchange momentum with these condensed phase fields and leave behind as they pass on to other fields down stream. By following repetitive elements in this model one will be able to put together a spatial and temperal compilation of the events happening in a two dimensional type chamber. This model should be quite capable of handling stable combustion processes as well as instabilities of a predominately transverse nature. It is not obvious at this time how this model might effectively be utilized to study longitudenal modes of instability. The model has the additional deficiency of not being able to provide its own initial conditions. Some prior information about the fields of streams and droplets and their locations, size and velocity distributions must be established. A preliminary simpler model must be used to provide initial distribution of condensed phase elements for the first few gas elements to move into and interact with.

INJECTION AND STREAM LOCATION

The experimental information which would be necessary to allow one to rigorously predict the location of the condensed phases of the propellants in the rocket chamber at any particular instant is grossly inadequate.

Given the injection conditions, in order to locate the condensed phases in the rocket chamber it will be necessary to estimate:

> the stream projections, their distortions and instabilities, the positional and time rates of drop shedding, the size distributions of the drops shed, the momentum exchange between the gas flow fields and the stream and the shed droplets and the rate of mass loss from the stream and droplets due to evaporation into the environment.

For a shower-head type injection the stream projection should proceed undisturbed except for stream instabilities and those instabilities introduced via aerodynamic interactions. For a completely laminar flow on ejection the stream should proceed undisturbed until subjected to sufficient aerodynamic forces to introduce surface instabilities alternately leading to stream break-up. In highly developed turbulent flow the rate of stream break-up due to its own internal flow instabilities should be very predictable. The former case is not a situation of practical interest or concern in a rocket motor system. The latter case has been used to study break-up of streams and impringing jets. Only on rare occasions however, have actual injectors been fabricated so as to produce streams with predictable degrees of internal turbulence by the time it is ejected into the combustion chamber. In the vast majority of the injector designs the length to diameter ratio is far too small to produce a predictable hydrodynamic state in the fluid stream as it exits from the injector face. Under these circumstances it is not infrequent that minor fabrication variances effect the gross behavior of the ejected stream more than the actual design parameters drawn up by the design engineer.

In distorted stream studies, again the vast bulk of work has been carried out with streams whose degree of internal disturbance at the time of leaving the injection device was unknown. In this area however, there has been studies carried out on paired injector systems in which sufficient L-D ratios were employed to have streams whose characterization was well established. With these systems, both the singular case of balanced momentum impringement and the more general cases of unbalanced momentum impringement have been studied. On this basis some qualitative information on fan spread and curvature has been established. Only one group has been found however, that has actually designed motor injectors on this principal so they could operate a motor with some reasonable a priori presumption about the true distribution of their propellants.

For impringement systems based on more than two streams or for distortion of streams based on splash plate techniques, the projection hydrodynamics of these streams are still a witches brew.

STREAM AND DROP BREAK-UP

A sizable portion of preliminary stream break-up (possibly all in the case of low aerodynamic influence) result from stream instabilities setting up dimenstional irregularies whose pattern predictability varies directly with the stream turbulence. The rate and location at which these instabilities occur has gone almost without investigation. The frequencies of these instabilities which well may set a pattern for the rates of arrival of concentrations of droplets size has been given some study. The addition of aerodynamic interaction with these surface instabilities frequently accentuates their degree as well as adding additional lateral movement or displacement to these elements. Asymmetric lateral displacements resulting from these aerodynamic interactions are frequently referred to as flag waving. This latter phenomena frequently photographed and/or qualitatively described, but has not been subjected to any rigorous treatment. This process is undoubtly an important element in the lateral displacement of shed droplets.

The shedding of droplets, from the main stream or fan as the case may be, is a continuous process in most practical injection systems continuing from the site of injection to the final exhaustion of the continuous stream. It is important to know at which point droplet elements are separated from the main stream and start interacting with the surrounding gases as independent entities. The actual work done in this area has been quite small, there have been a few studies of the rate of attrition from streams subjected to short pulses of high gas flows perpendicular to the stream and there have been a few very small studies of the rates of shedding of microdrops from the larger drops as a result of high loading rate aerodynamic shear.

The size distribution of drop shed either from impringing stream produced fans or from individual streams subjected to aerodynamic break-up represents one of the brighter areas in this field. These studies, however, have been restricted to total pictures of accumulated distribution of sizes. There is essentially no information on locational differences in size distribution from early or late stream or fan break-up or how much variation there is in size distribution associated with the differences in periodic wave fluctation so prevalent in many fan and stream break-up patterns.

Aerodynamic break-up of droplets has been looked at very extensively. This process has been photographed and defined into three different regimes based on the relationship of the aerodynamic loading and the internal cohesive forces of the droplet. There has been some effort in these studies to provide at least qualitative information on the times to break-up of the original droplet. There has been relatively little effort on the more important problem of the relative rate of the generation of new surface or the rates of formation of new droplets and their size distributions.

MULTIPLE PHASE TRANSPORT AND DISPERSION

Momentum exchange between the gaseous and the condensed phased elements affects both the processes of the breaking up of larger condensed phase elements and their displacement from their original velocity vectors. The roll of aerodynamic interaction in the break-up in the condensed phase elements has already been discussed above. The roll of two phase transport in dispersion will be examined here.

The drag effects of a fluid flowing at a fixed relative velocity passed a rigid sphere have been very well worked out. The drops in a rocket combustor are "free floating" units with continually changing relative velocities and accelerations. Even assuming the case of rigid spherical particles there is still a considerable scatter of experimentally estimated drag coefficients over a broad range of Reynolds numbers under these conditions. For aerodynamic loading producing webbers numbers of say half an order of magnitude less than the critical number for bag break-up, the oscillations in the droplet shape due to the aerodynamic drag forces are sufficiently small so that the treatment of the system as average rigid spheres is quite reasonable. In some low mass through-put high contraction ratio rocket chambers the relative velocities are quite frequently low enough so that is not unreasonable to treat droplet sizes up to a hundred microns as though they were rigid spheres. The relative velocities occurring in some of the extremely high mass through-put, low contraction ratio chambers push this size limit down to more nearly 10 microns.

In a large number of rocket chambers a sizable fraction of the droplets are subjected to sufficient aerodynamic loading to distort them well out of the conventional drag coefficient values estimated for rigid spheres. Many of these droplets would, if they survived long enough, either be distorted to bag formation and subsequent break-up or be more directly subjected to surface shear break-up. There have been some programs which have developed pseudo-drag coefficients based on original droplet diameters. There have been other studies which have attempted to actually elucidate some sort of a drag coefficient for the pessary and cup shape structures which appear to be developing under these heavy loading conditions. In rocket combustion activities, the generation of droplet surface for evaporation, is an important rate limiting step. These processes which are simultaneously responsible for the more rapid generation of new surface as well as relatively rapid change in position of these elements will be of crucial importance in the development of a rigorous model of rocket combustion processes.

Considerably less effort has been found on the displacement of the continuous stream elements by aerodynamic forces than on droplet studies. Lateral displacement of single jet streams have been studied, however, these studies have been related to break-up studies and the effort spent on analyzing the stream trojectory has been minimal. The effect on gas drag on streams flowing parallel or near parallel with the gas flow have been studied most exclusively in terms of the stream break-up. No mention has been found at this point in the search of any studies of momentum transfer from the gas to liquid main streams.

COMBUSTION PROCESSES

Droplet combustion has been studied for bipropellant situations on stagnant conditions at zero G loadings, under conditions of natural convection, and under a variety of free fall conditions at or near one atmosphere pressure. Suspended droplet burning studies have been carried out at chamber pressures up to twenty atmospheres. Free droplets have been studied while burning under flow conditions up to and exceeding critical Webber numbers loading, in environments of one to six atmospheres pressure. Porous spheres and cylinderical rod stabilized surfaces and surface dish burning of liquid propellants have been examined at pressures from one to ten atmospheres. Under flow conditions up to a Reynolds number of 10,000 under both study state and oscillatory conditions. There is a great paucity of studies of drop or other burning elements under conditions exceeding twenty atmospheres leaving those very important regimes approaching, passing and exceeding the critical pressures virtually unexplored. Virtually all the above studies have been carried out with one liquid element suspended in a semi-infinite atmosphere of the other propellants as a gas. There have been some studies in which the gaseous element was diluted with an inert diluent.

In a chamber where the bipropellants are injected with a system of like-on-like impinging jet, the break-up of the particular propellant occurs where the local situation is dominated by that particular propellant. This means that a sizable fraction of the fuel droplets, in a rocket, are not going to burn in semi-infinite atmosphere of oxidizer gas but rather will be burning in an atmosphere of fuel rich gas and combustion products and analogously the oxidizer droplets will not be burning in semi-infinite atmosphere of fuel but will be burning in an oxidizer rich atmosphere containing combustion products. These situations have not been given appreciable study in under heterogeneous conditions. One is, therefore, left at this time to try to build rocket combustion models for unmixed bipropellant systems with no real experimental information on the processes of droplet combustion as they are most likely to be occurring. Combustion studies have been carried out in droplet spray fields. The results of these studies are compatible with the assumptions of combustion driven flow and wave fields and the shattering of droplets in these high velocities fields. These studies have not as yet been given rigorous analysis.

Monopropellant combustion studies have been carried out on droplets, porous spheres, and exposed liquid surfaces. Neither as wide a variety of these materials has been studied nor have they been studied under the variety of conditions which have been employed for the examination of bipropellant type systems. Again, like the bipropellant system, the amount of combustion studies have for the most part been carried out under conditions which do not simulate those found in a rocket motor. Typically the monopropellant is allowed to burn in a semi-infinite cool atmosphere of an inert gas.

In the bipropellant liquid system, it is assumed to be reasonable to treat the consumption of droplets and other condensed phase elements as though they are independently being consumed with their own local flame interaction with their own local environment. One must still recognize the point that this has not accomplished the complete combustion and ultimate energy release for these propellants. Each fan projection in these systems is a localized oxidizer rich or fuel rich gas generation system. Further energy release will result from the turbulent gas mixing between the zones. In rocket combustion studies per se, this step has been given essentially no consideration to date. There has been developed a modest body of information on turbulent gas mixing and flames associated therewith. In the case of high mass through-put low contraction ratio engine systems there is substantial photographic evidence to show that this subsequent mixing is by no means completed by the time the gases reach the exit plane.

Propellant combustion performance calculations have been carried out for an extremely wide variety of bipropellant combinations over very wide mixture ratios for equilibrium conditions. The literature is literally inundated with this type of calculation, however under many off mixture ratio conditions equilibrium values simply are not approached. Not infrequently this results in the production of fragments that are refractive to more complete combustion when subsequent turbulent mixing brings the local mixture ratio closer in line with the over all design value. Thus, while in the gross, the kinetics of most of the reactions which are occurring in our major bipropellant rocket systems are orders of magnitude faster than the rate limiting physical phenomena, there appear to be numerous areas of local, kineticly inhibited situations which impose ultimate limitation on the total C* values realized. In the case of many cool burning combustors designed primarily for driving turbines, the kinetic limitations are so great as to make performance and composition calculations based on equilibrium assumptions meaningless.

COMBUSTION SUPPORTED WAVES

Of all the fields of supporting information leading to the gross understanding of rocket motor combustion processes that area of combustion supported waves and wave phenomena has been both the most extensively studied and the least effectively tied to rocket e gine combustion processes. A number of situations of premixed gas combustion, generating waves have been studied and extensively photographed or described. When a small discreet volume of premixed gas burns uniformly with diffuse heat addition it drives flow fields and pressure waves ahead of its moving contact surface. This expanding gas element maybe readily treated as though it were simply driving a piston of infinitesimal thickness at its contact surface against the outside gases.

The next step in complexity is that of flame propagating down a tube of premixed gases. If one could start out with ignition across a planar front, this flame front would, at its onset, start progressing down the tube at the linear burning rate of this particular gas mixture. However, as soon as the flame front had progressed a finite distance we would have accumulated behind the flame front hot pressurized gases which would now start acting as a hot gas piston pushing both the flame and the gases ahead of the flame front downstream. The flame front will now be moving into gases which already have a forward velocity so that the flame front appears to be accelerating relative to a stationary point of reference but at this point it is not accelerating relative to local gas particles downstream of the flame. The gas velocities in front of the flame front however, are being accelerated due to pressure driven flow fields setting up a shock front ahead of the flame front with flow fields between the shock front and the flame front itself. The viscous behavior of the gas will set-up velocity gradients which the flame front will follow generating a more extended burning service and producing a higher rate of pressure and energy generation. This becomes a progressive situation with a positive feedback. Accelerating laminar flow gives way to turbulent flow which even more rapidly increases the extent of the flame front surface and the dept of involvement. This situation proceeds until the mechanical energy pushed into the flow fields between the flame zone flow and the shock front is raised to a point that nearly simultaneous combustion occurs throughout this zone and a stablized detonation wave is established subsequently down stream. Having reached a stablized detonating condition we now are again in a regime in which rigorous analytical calculations may be made and verified by experimental studies. It is in this intermediate area between when the laminar flame ceases to be a planar phenomena up until the establishment of a stablized detonation for which there is an acute lack of analytical treatment. It is this authors opinion that it is this intermediate transition zone which most nearly corresponds to the phenomena occurring in a liquid rocket engine. The growth of individual waves as a result of combustion processes in a heterogeneous field has been studied in a spray fields, dust fields and through porous solid beds. This area, however, has not been brought to the point wherein a rigorous analytical treatment can effectively and predictably describe this phenomena in general.

The simpler case, however, where localized energy addition will drive waves or maintain standing waves has been developed to a considerably greater extent. The simplest of these situations is probably the driving of an organ pipe resonance with a heated screen at one end of a tube. Of a similiar nature are those systems in which longitudenal oscillations are driven in premixed gas motors of high L*. In general the flame front is very shallow and very close to the injector face. The heat source can be treated essentially planar and one might almost consider this equivalent to passing cold gas over a heated screen with nearly infinite heat flux capabilities with the subsequent heated gas flowing outward through the resonance chamber.

There have been numerous studies of wave attentuation in heterogeneous systems. These studies have included both sound field and finite insensity wave attentuation studies.

The range of media from heterogeneous unmixed turbulent gas flow fields to dust spray aerosol or droplet entrained fields, in a gaseous medium through the complete range of two-phase gas liquid fields gas fields as well as an extensive variety of gas solid fields have been studied. Loss factors for individual finite waves, propagation through a wide variety of size and concentration regimes, appear to be extensively studied. From the abstracts which have been surveyed thus far no one has attempted to break out the causes of loss factors such as a relative contribution of mometum exchange and/or wave defraction in these heterogeneous systems. These studies on finite wave attenuations have been carried out on individual waves. No similiar studies have as yet been found on heterosperse fields of finite waves.

There are an extensive body of studies on finite wave interactions with waves and with other discontinuities. These studies have covered weak intermediate and strong finite waves, including the interactions, squarely or obliquely, with compressive waves, expansive systems, flame fronts and other discontinuities.

The problems of diffuse energy additions appear to have been satisfactorily treated, if it can be assumed that one is dealing cell by cell with a sufficiently small cell that the rate of energy addition throughout the cell is not grossly different than some average value taken for that element.

The problem of mass loss through diffusion to the wall of the system or via condensation to condensed phase elements has been treated. However, the converse problem of mass addition to the gas stream has not been treated because of the inherent problems of converting a one dimensional problem into a two dimensional problem. It does seem to be distinctly possible within the available analytical approaches to treat the problem of mass transfer from the condensed phase to the gaseous phase. If this is considered to be done on a sufficiently diffuse basis that, for the cell under consideration, the over all one dimensional characteristics of the flow are not grossly disturbed.

It would appear therefore, that the problems of introducing combustion supported wave analysis into an overall rocket combustion model are not primarily those of a serious or gross deficiency of the basic parts but rather are ones of the monumental effort of fitting rather numerous detailed pieces together in order to describe such a complex and variable system. The flow phenomena associated with these processes may be readily expressed in the form of eliptical differential equations. While these forms are not readily amendable to easy analytical solution there are well establish-ed graphical techniques for the treatment of these phenomena as they occur as individual events. The problem of treating this more complex system appears to be one of working out a sufficiently adequate bookkeeping system in order to continuously keep tract of the multiple components of a large number of small cells.

MISCELLANEOUS

There are several areas which were covered in the general outline presented in Progress Report No. II of this series which have not been reviewed to this point.

The effects of flow conditions leading up to the entrance to the rear side of the injector may well have significant contributions to the flow patterns of the jet streams entering into the chamber.

There has been an increasing interest in an experimental studies of two phase propellant injection systems. These include gas liquid systems in which gas is added to modulate the propellant flow in a bipropellant system. Solid-liquid system slurries and solid powders entrained in gases have been considered over a number of years and are still being actively considered as means of increasing the heat release functions of the propellants during combustion. While all these multiple phase flow systems have markedly altered fluid characteristics in regard to break-up and dispersion patterns which undoubtly have major bearings on the combustion efficiency and stabilities there have been virtually no studies of these basic problems but rather the systems have been studied predominately in model motor firings.

Propellant properties have not been reviewed on a propellant by propellant basis. The problems of chamber geometry have not been considered in this discussion. Throughout this discussion it has been assumed that we were dealing with a model selected from a conventional chamber geometry with monotonic flow. It is not believed that this model would be applicable, for example, for a toroidal shaped chamber whether for reverse flow or for a spike-type nozzle.

SUMMARY

A number of major information gaps can be listed at this time as the result of the preliminary review of the abstracts (more than 5,000) which have been received to date.

1. Injection and Stream Location:

   There is inadequate fluid dynamic characterization of the streams effluxing from most injectors.

   There is a scarcity of quantitative information on stream distortion behavior.

2. Stream and Drop Break-up:

   There is no data to speak of on the time or positional rates of stream and drop break-up.

3. Multiple Phase Transport and Dispersions:

   There are no well developed drag coefficients for accelerating particles in variable relative velocity fields.

   There has been no effective development of drag coefficients of rapidly distorting drops.

   The displacement of streams by aerodynamic loading has been only sparsely studied.

   The aerodynamic accentuation of stream instabilities has been qualitatively described but not treated quantitatively.

4. Combustion:

   Drop burning studies need to be executed in the near, trans, and supercritical pressure regimes.

   Drop burning studies need to be executed in the off mixture ratio regimes which occur in fuel or oxidizer fans.

   Non-equilibrium "performance" calculations should be explored for these off mixture-ratio regimes.